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THE ABSOLUTE SPECTRA OF GALACTIC COSMIC RAYS AT SOLAR MINIMUM AND THEIR IMPLICATIONS FOR MANNED SPACE FLIGHT

J. H. Adams, Jr.[1], G.D. Badhwar[2], R.A. Mewaldt[3], B. Mitra[4], P.M. O'Neill[2], J.F. Ormes[4], P.W. Stemwedel[1], and R.E. Streitmatter[4]

ABSTRACT

The radiation dose from galactic cosmic rays during a proposed mission to Mars is near the annual dose limit for the crew. Since the absolute spectra of galactic cosmic rays critically influences mission planning and spacecraft design, these spectra must be determined as accurately as possible. We have fit published measurements with solutions of the spherically symmetric diffusion equation to make accurate representations of the spectra. We report preliminary determinations on the absolute differential energy spectra at 1 AU and discuss the implications for the proposed missions to Mars.

Introduction: In the USA and other countries plans are being made for manned missions to explore Mars (e.g. see Stafford et al. 1991). Stafford et al. have investigated several Mars missions using both chemical and nuclear thermal propulsion. All these required round trip travel times of approximately one year. The annual radiation dose-equivalent (DE) limit for US astronauts (NCRP 98, 1989) is 0.5 Sieverts (or 50 REM) per year at a depth of 5 cm in tissue. Letaw, Silberberg, & Tsao (1988) have shown that this limit is reached by galactic cosmic rays (GCRs) alone at solar minimum. Their calculations also show that while the DE at solar minimum can be reduced to about 0.33 Sieverts (Sv) by 10 cm of aluminum shielding, additional shielding produces little reduction. As a consequence, small uncertainties in the GCR flux lead to large uncertainties in the amount of shielding required to protect the crew (Simonson and Nealy 1991). These considerations make it critically important to know the spectra of GCRs accurately.

Behind realistic shielding configurations 80% of the DE is due to H, He, C, O, Ne, Mg, Si, and Fe nuclei that have energies between 0.02 and 20 GeV/nuc (Simonson and Nealy 1991), so we have concentrated on these elements. The Cosmic Ray Effects on MicroElectronics (CREME) model (Adams 1986, and references therein) is commonly used to represent the GCR spectra in calculations of dose equivalent. Our comparisons of CREME spectra with the historical data base show errors as large as 70% below 5 GeV/amu. When CREME is used to predict spectra at a specific time in the future, there is additional uncertainty due to the lack of repeatability of the solar cycle. We expect errors of 50% in CREME predictions of future fluxes.

Method: We have surveyed the literature to find all published measurements of absolute fluxes of GCRs for the elements listed above. We have found 176 published measurements from observations made between 1956 and 1987. In early measurements only H and He were resolved with heavier ions measured in elemental groups. We have used measured elemental ratios to correct these measurements. After 1967, measurements of elemental spectra between 0.02 and 20 GeV/nuc are reported. We report here on fits to data after 1964. For the elements He, O, and Ne we have restricted the data to E > 50 MeV/nuc to avoid anomalous cosmic rays.

[1]Code 4154, E.O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375-5000 USA.
[2]Mail Code SN3, NASA Johnson Space Center, Houston, TX 77058 USA.
[3]California Institute of Technology, Pasadena, CA 91125 USA.
[4]Code 660, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

To construct a better representation of the GCR elemental spectra, we define heliospheric boundary spectra and use solar modulation theory to describe the spectra between Earth and Mars. An accurate description of solar modulation requires that gradient and curvature drift effects (Jokipii, Levy, & Hubbard 1977) be taken into account. We have found, however, that the data can be reasonably well represented by the spherically symmetric Fokker-Planck equation that includes the effects of diffusion, convection and adiabatic deceleration (e.g. Gleeson & Axford, 1967). We have solved the Fokker-Planck equation using the method of Fisk (1971), where the functional form of the diffusion coefficient, K_d, was taken to be

$$K_d = \beta P K,$$

following Garcia-Munoz, Pyle, & Simpson (1985), where P is the magnetic rigidity in GV, β is the velocity in units of c and K is a function of time. We restricted our fits to energies above 45 MeV/nuc, avoiding the anomalous component and the dependence of K_d on energy at low energies. We use a boundary of 50 AU and a solar wind speed of 400 km/sec, but suppressed the radial dependence in K_d through our choice of K. We used the work of Tang (1990) as a starting point for the local interstellar (LI) H and He spectra, checking them with data at high energies. At lower energies we adjusted the spectra to a form which gave best fits to the measured H and He spectra over the period 1965-87 by varying only K(t).

The LI spectra for O and Fe were obtained by starting with Tang's LI Fe spectrum and K(t) determined above. The LI spectra were adjusted to get the best fits to all the O and Fe measurements from 1965 to 1987. K(t) determined from the H and He measurements was found to represent the measured O and Fe spectra over the 1965-87 period. Fig. 1 shows the K(t) values we determined. In Fig. 2 we show the LI spectra for H, O, and Fe and our representations for these spectra at 1 AU during 1977. In fig. 3 we compare Fe spectra from our model and CREME. The minima and maxima of the 20th and 21st solar cycles are different. We have compared CREME and our model with the measured Fe spectra below 5 GeV/nuc by computing χ in each year where data are available. We find that reduced χ^2 for CREME varies from 0.13 to 0.70 with a typical value of 0.35, while our model varied from 0.06 to 0.28, with a typical value of 0.10. This improvement is due primarily to replacing CREME's sinusoidally varying solar modulation model with K(t) fitted for each of the years in the historical data base, thus accounting for differences in solar cycles. There will be additional uncertainty in predictions of future spectra using our model. Our method and the results are described in more detail by Badhwar and O'Neill (1991).

Calculation of the Dose Equivalent: We have used our spectral representations for the 1977 solar minimum to calculate the DE versus shielding depth (Fig. 4), following the methods of Letaw, Silberberg, & Tsao (1988) with the current definition of Q (ICRU-60, 1991). Our preliminary results indicate the dose equivalent for the 1977 solar minimum exceeds the current limit for less than 7.5 cm of aluminum shielding. This increase is due to both the higher cosmic ray flux in 1977 and the new definition of Q. Also shown in Fig. 4 is the upper bound on the DE for 1977 at a 90% confidence level (from the typical χ^2 of 0.10 for our model). This result indicates that 16.5 cm of aluminum shielding is needed to be certain of not exceeding the 0.5 Sv limit at the 90% confidence level for a mission conducted in 1977.

Conclusions: A representation of the GCR flux since 1965 has been developed with an accuracy of 10%, typically. We have used this representation to calculate the DE in 1977. We conclude that it is difficult to be certain of keeping the DE below 0.5 Sv on a journey to Mars of a year or more, with the galactic cosmic rays at the 1977 flux levels, since some allowance is needed for the DE from solar energetic particle events. Predictions of the DE on future missions to Mars will have additional uncertainties which have not been quantified. Further work is necessary to make accurate predictions with known uncertainties. We must sample solar modulation over the longest possible time period to learn the range of fluxes to be expected in the future.

The uncertainties due to cross section errors must be included in calculations of the 90% confidence level. Realistic estimates must also be made of the DE from solar energetic particles in order to determine how and when manned missions to Mars can be made safely.

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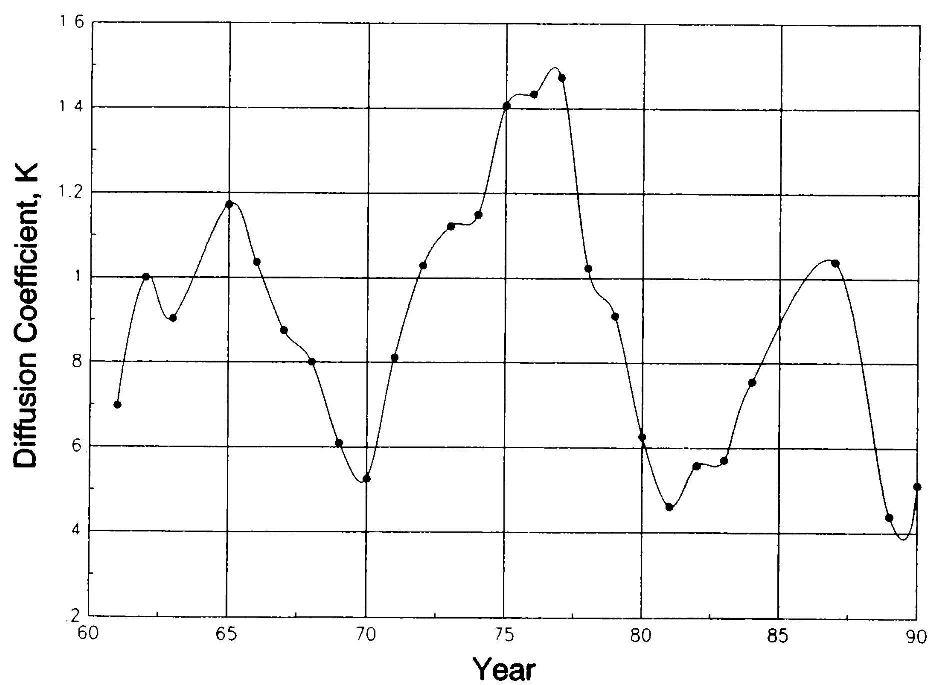

Fig. 1: The diffusion coefficient of K(t) that we have determined as a function of time. K(t) is in units of 1.507×10^{22} cm^2/sec.

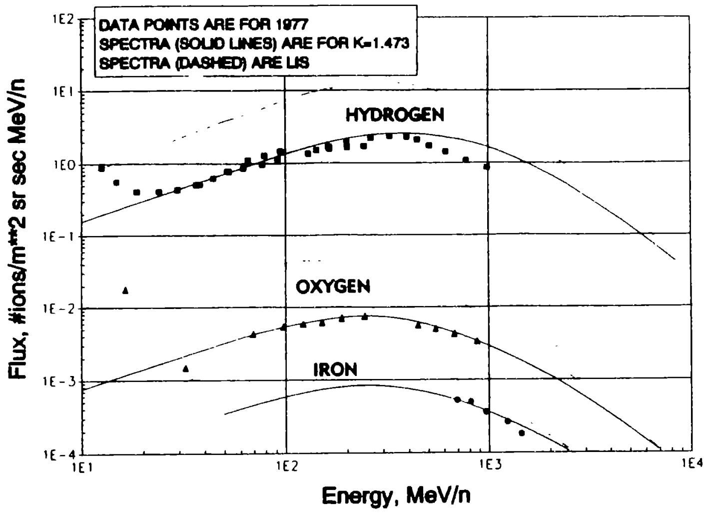

Fig. 2: The local interstellar spectra for H, O, and Fe and measured H, O, and Fe spectra compared with our representations in 1977. The H data come from Evenson et al. (1983), Von Rosenvinge et al. (1979) and Webber and Yushak (1979). The O data come from Mason et al. (1979) and Garcia-Munoz (1977) and the Fe data come from Young (1978).

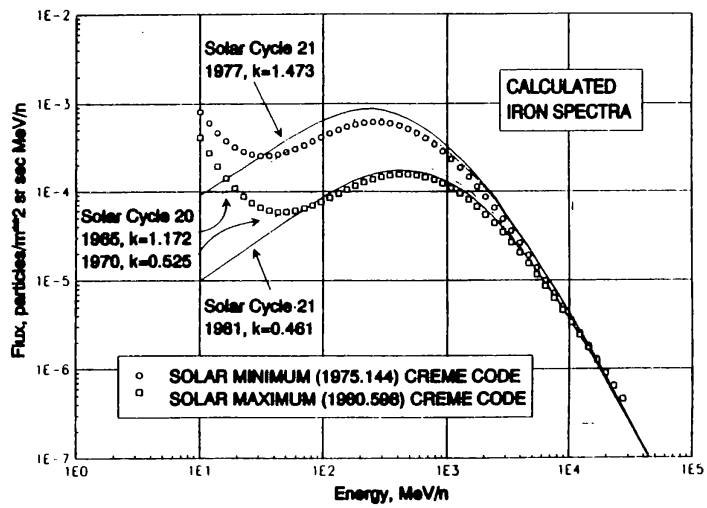

Fig. 3: Our representations of Fe spectra for the extremes of the 20th and 21st solar cycles compared with CREME spectra.

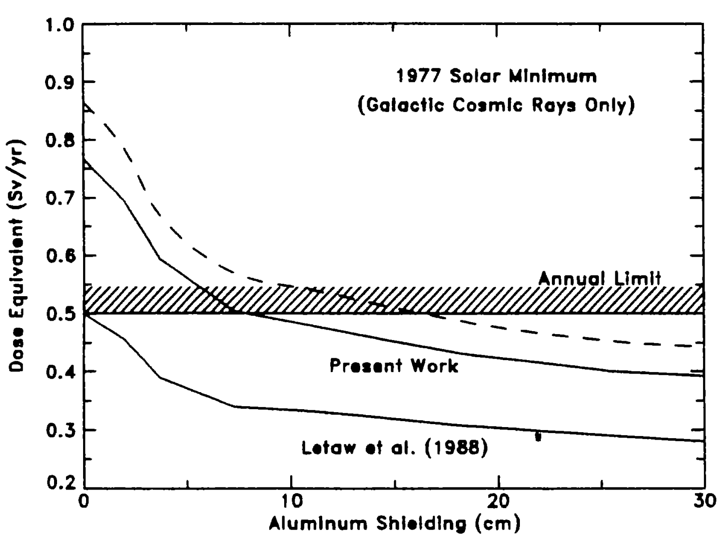

Fig. 4: The dose equivalent at a depth of 5 cm in tissue versus aluminum shielding depth during the 1977 solar minimum. Results from the present work are compared with those of Letaw et al. (1988). Our results predict higher dose equivalents because they more accurately represent the galactic fluxes in 1977 and because of the new definition of Q. The dashed curve is an upper bound on the dose equivalent at the 90% confidence level, based on the present work.